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Heating of the Solar Corona by Dissipative Alfvén Solitons

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Solar photospheric convection drives myriads of dissipative Alfvén solitons (hereinafter called alfvenons) capable of accelerating electrons and ions to energies of hundreds of keV and producing the X-ray corona. Alfvenons are exact solutions of two-fluid equations for a collisionless plasma and represent natural accelerators for conversion of the electromagnetic energy flux driven by convective flows into kinetic energy of charged particles in space and astrophysical plasmas. Their properties have been experimentally verified in the magnetosphere, where they accelerate auroral electrons to tens of keV.

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Understanding the mechanisms that heat plasma in the solar corona to temperatures of millions of Kelvin has been a long standing problem in solar physics. The early view was that the convection in the photosphere produces sound waves, internal gravity waves, and magnetohydrodynamic waves which propagate upward to the solar corona and deposit their energy to the ambient gas. Later, it was realized that all but Alfvén waves are dissipated and/or refracted in the chromosphere and in the transition region before reaching the corona [1, 2, 3, 4]. The electromagnetic energy driven by convective flows can be transported along the magnetic field as Poynting flux of Alfvén waves. However, Alfvén waves are disinclined to dissipate in collisionless plasmas, and the main problem was to explain how this energy flux is deposited locally to heat particles in the solar corona [5]. During the last 50 years there have been many attempts to solve this outstanding problem in astrophysics, and there are more than 20 different models and mechanisms for coronal heating proposed in the literature; see reviews [6, 7, 8].

In this Letter I show that two-fluid equations for a collisionless plasma have nonlinear solutions in the form of dissipative Alfvén solitons (alfvenons), which represent filamentary space charge structures with strong perpendicular electric fields and large parallel potential drops. Alfvenons will form spontaneously when a magnetohydrodynamic perturbation propagates upward in the solar corona where the Alfvén speed decreases. They represent natural plasma accelerators for converting electromagnetic energy flux driven by convective flows to kinetic energy of charged particles on spatial scales related to the ion inertial length $\lambda_i = c/\omega_{pi}$, where c is the speed of light and ω_{pi} is ion plasma frequency. Alfvenons can provide an explanation for various aspects of electromagnetic energy dissipation and heating in the solar corona and in the planetary magnetospheres.

Consider the geometry of magnetic fields in the solar corona depicted in Fig. 1. It shows magnetic field lines (blue) inclined at angle α from the wave propagation direction x. There is a transverse flow with speed V_h in the z direction, associated with the electric field $\mathbf{E} = -\mathbf{V}_h \times \mathbf{B}$. This geometry implies that the photospheric convection drives electromagnetic energy flux $\mathbf{S} = \mu_0^{-1}\mathbf{E}\times\mathbf{B}$ with an upward component $S_x = \mu_0^{-1} V_h B^2 \sin\alpha\cos\alpha$. Dragging of magnetic field lines by variable convection of a conductive plasma induces magnetic stresses propagating along $\mathbf{B}$ with Alfvén speed $V_A = B(\mu_0\rho_i)^{-1/2}$, which implies that $\sin\alpha = \langle V_h\rangle/V_A$. The upward energy flux carried by Alfvén waves driven by convection $\langle V_h\rangle$ is then

$$S_x = (\rho_i/\mu_0)^{1/2}\langle V_h\rangle^2 B\cos\alpha. \qquad (1)$$

This form of the energy flux is consistent with an em-

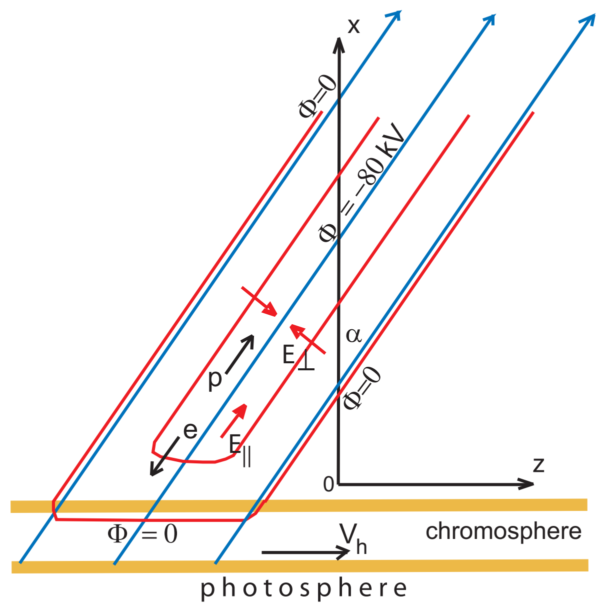

FIG. 1: Geometry and coordinate system for a wave structure (alfvenon) propagating along x at angle α to the magnetic field (blue lines), and driven by convective flows in the photosphere. The electric potential structure (red lines) would accelerate electrons toward the chromosphere and ions out of the chromosphere. The angle $\alpha = \sin^{-1}(V_h/V_A)$ is small.

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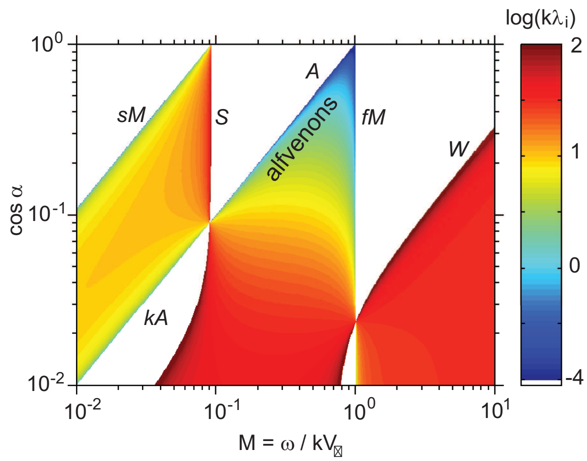

FIG. 2: Occurrence region of nonlinear waves in two-fluid theory for plasma $\beta = 10^{-2}$, with marked position of alfvenons. Color coded is $\log(k\lambda_i)$, the exponential growth rate of nonlinear waves. White regions are occupied by linear waves.

pirical relation between the total energy deposition and photospheric magnetic flux in active regions, $S_x \propto B^\kappa$ with $\kappa \approx 1$, while $\kappa \approx 2$ should be observed if the energy dissipation was related to reconnection of tangled magnetic field lines [9]. It is estimated that an average upward energy flux of 10^7 erg cm^{-2} s^{-1} is sufficient to account for energy deposition in the solar corona [1]. For the magnetic field $B \approx 100$ G and photospheric density of $\rho_i = 10^{-7}$ g cm^{-3}, a convection speed as small as $V_h = 0.5$ km/s provides Poynting flux exceeding 10^7 erg cm^{-2} s^{-1} (10 kW m^{-2}). It is therefore justified to assume that the electromagnetic energy flux of Alfvén modes driven by the photospheric convection ($V_h > 0.5$ km/s) is sufficient to power all processes in the chromosphere and the solar corona. It will be shown below that the dissipation mechanism for this Poynting flux can be provided by nonlinear Alfvén structures similar to those observed in association with auroral acceleration.

The height distributions of the background magnetic field $B(x)$ and of ion density $\rho_i(x)$ in the solar atmosphere is such that the Alfvén speed decreases with x from a maximum value inside the chromosphere [8]. It is known that Alfvén waves can become evanescent or nonlinear if they propagate in a region of decreasing Alfvén speed [10]. One expects then formation of nonlinear Alfvén waves (alfvenons) at some altitude in the corona. From the general dispersion equation for a two-fluid plasma model one can determine the locations of nonlinear waves in the phase space (M, α), where $M = V_{x0}/V_A = \omega/kV_A$ is the alfvenic Mach number. Figure 2 shows portraits of the exponential spatial growth rate $k\lambda_i$ of nonlinear waves [10]. White areas in Fig. 2 correspond to the well known linear waves: slow magnetosonic (sM), sound (S), Alfvén (A), kinetic Alfvén waves (kA), fast magnetosonic (fM), and whistler modes (W). The position of the sound line (S) is determined by the sound speed $V_s = (\gamma\beta/2)^{1/2} V_A$, where γ is the polytropic pressure exponent and β denotes the ratio of plasma/magnetic field pressures. A linear Alfvén wave from region A in Fig. 2 can tunnel to the nonlinear alfvenon region (below the line $M = \omega/kV_A(x) = \cos\alpha$), if $V_A(x)$ is decreasing along the wave path.

In a low beta plasma, details of the pressure model [11] are not relevant and the electron inertia is not important for modes propagating quasi-parallel. The governing equations for a magnetohydrodynamic structure propagating along x can be written in a stationary wave frame as [10, 12]

$$\frac{\lambda_i}{M_\alpha}\frac{\partial b_y}{\partial x} = b_{z0}(n-1) - b_z\left(1 - \frac{n}{M_\alpha^2}\right), \quad (2)$$

$$\frac{\lambda_i}{M_\alpha}\frac{\partial b_z}{\partial x} = b_y\left(1 - \frac{n}{M_\alpha^2}\right), \quad (3)$$

$$\frac{\partial n}{\partial x} = \left(\frac{M_0^2}{n^2} - \frac{\gamma\beta}{2}n^{\gamma-1}\right)^{-1}\left[b_y\frac{\partial b_y}{\partial x} + (b_{z0}+b_z)\frac{\partial b_z}{\partial x}\right], \quad (4)$$

$$e_x = -M_0 b_y \tan\alpha - \frac{\gamma\beta_e}{2}\lambda_i\frac{\partial n^\gamma}{\partial x}, \quad (5)$$

with $M_\alpha = M_0/\cos\alpha$, $\beta = 2\mu_0 p_0/B_0^2$, $b_{z0} = \sin\alpha + g(x)$, where $g(x)$ represents a weak gradient of the background magnetic field, which can be used to study the transition between the linear and nonlinear regimes. Subscript '0' denotes background quantities at the starting point x_0. The magnetic field is normalized with B_0, the electric field $e_x = E_x/V_A B_0$, and $n = N/N_0$ is the ion number density. Equations (2)-(5) represent a complete set of fully nonlinear Hall-MHD equations for field variables b_y, b_z, n, e_x. Note that $b_x = \cos\alpha$, $e_y = M_0 \sin\alpha$, $e_z = 0$ are constant, $g(x_0) = 0$, and the variations of the background density due to gravitation are neglected.

The above equations describe linear (sinusoidal) as well as nonlinear (cnoidal) waves, including solitons, in branches: slow/fast magnetosonic, Alfvén, acoustic, and kinetic Alfvén waves. They are easily integrated with an initial perturbation δb_z, implying the boundary values: $b_y(x_0) = 0$, $b_z(x_0) = \delta b_z$, $n(x_0) = 1 + (M_0^2 - \gamma\beta/2)^{-1} b_{z0}\delta b_z$. Figure 3 shows exact solutions for the electric field E_x, and the electric potential $\Phi = -\int E_x dx$. The magnetic signatures and field-aligned current associated with this structure are shown in Fig. 4. The structure has an oppositely directed electric field ($\nabla \cdot \mathbf{E} < 0$) with a negative potential in the center, i.e. it is an ion hole. The total magnetic field has a small depression correlated with the density depression. The computations were made in dimensionless variables and converted to physical units using typical values measured in the corona: $B \approx 10$ G and $N \approx 10^8$ cm^{-3}, which imply $V_A \approx 2000$ km/s, and $\lambda_i \approx 20$ m. The computed electric field can be schematically presented as equipotential (red) lines shown in Fig. 1. It is seen that the magnetic field lines external to the structure have potential equal to zero. The chromospheric potential is also zero because it is along the convection streamlines. However, the center magnetic field line is at a large negative potential (−80 kV in Fig. 3), implying the existence of a parallel

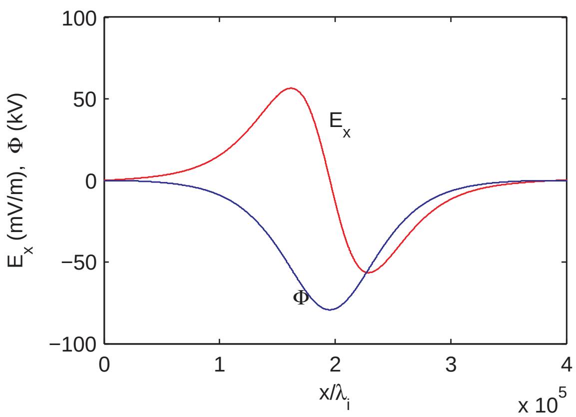

FIG. 3: Exact solutions of equations (2-5) for an alfvenon propagating at angle $\alpha = 0.5°$. Medium parameters: $B_0 = 10$ G, $N_0 = 10^8$ cm^{-3}, $\beta = 10^{-2}$, $\gamma = 1.6$, and $\lambda_i = 20$ m.

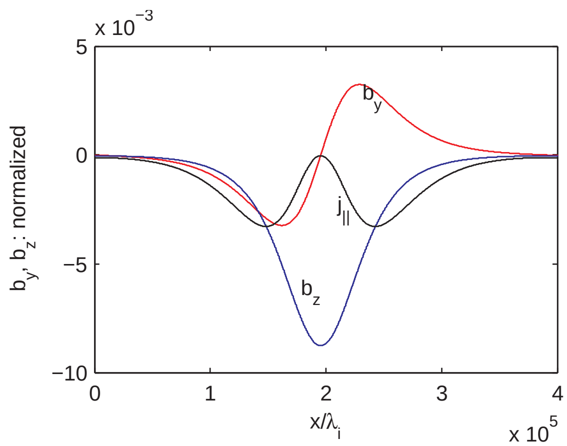

FIG. 4: Field-aligned current density $j_{\|}$ (arbitrary units, $j_{min} = -2 \times 10^{-8}$ A m^{-2}), and transverse magnetic field perturbations (b_y, b_z, normalized with B_0) for the alfvenon in Fig. 3.

potential drop equal to the perpendicular potential drop. Conservation of total energy of a particle (kinetic + electric potential) implies that an electron leaving the structure along the magnetic field lines to the chromosphere will acquire kinetic energy equivalent to $e\Phi(x)$, producing X-rays when interacting with the ambient gas. Similarly, an ion from the chromosphere entering the structure would be accelerated upward by the same potential $\Phi(x)$. Mathematically, this nonlinear structure is formed as a result of a balance between nonlinear growth and dispersion related to terms with ion inertia λ_i in the governing equations (2)-(5), and therefore it could be regarded as a soliton. However, connection with the conducting chromosphere introduces a dissipative element to this soliton. Its energy would dissipate by acceleration of electrons toward the chromosphere and ions out of the chromosphere. Alfvenons form filamentary structures with extension along the magnetic field much larger than the perpendicular size. In the example of Fig. 3, the length of the alfvenon is $L \sim 3 \times 10^5\,\lambda_i \approx 6000$ km, while the width $L_\perp \approx L \sin\alpha \approx 50$ km. The length of the alfvenon would increase (decrease) with decreasing (increasing) angle $\alpha = \sin^{-1}(V_h/V_A)$.

Let us estimate the electric field available for acceleration of charged particles in alfvenons. From Eq. (5) we find that $E_x \approx -MV_AB_y \tan\alpha$. A typical magnetic polarization pattern for alfvenons, which can be found from numerical solutions, is rotation of the transverse magnetic field (B_y, B_z) around the guiding B_x field such that $|B_y|_{max} \sim B_{z0} = B_0 \sin\alpha$. Furthermore, alfvenons are formed near $M \approx \cos\alpha$ (see Fig. 2), which implies

$$|E_x|_{max} \sim V_A B \sin^2\alpha. \qquad (6)$$

As is seen, the electric field in an alfvenon depends on the propagation angle and can vary from zero (parallel propagation) to the maximum value of $E_A = B_0V_A$ for perpendicular propagation.

The electric potential structure obtained here in a self-consistent way (though in a simplified geometry) is not a speculative result awaiting observational verification. In fact, the presence of such electric potential structures above the aurora was first inferred from satellite measurements 30 years ago [13]. Properties of these U-shaped auroral acceleration structures have been thoroughly investigated in numerous publications listed in a recent review of auroral processes [14], but until now there was no theoretical model for these structures. Thus, the alfvenons described in this Letter provide also an explanation for the U-shaped auroral potential structures. Particle measurements inside these acceleration structures show upward directed ion beams associated with electrons accelerated downward by the electric potentials 1-20 kV, and forming so-called inverted-V structures in energy versus time flux-spectrograms. An obvious difference between the solar corona and the magnetosphere is that in the first case the driving convection is applied to the bottom end of the flux tubes in Fig. 1 (in the photosphere), while in the second case to the top end (in the distant magnetosphere). The magnetospheric alfvenons are created below an altitude of 1 R$_E$, i.e. in region where the Alfvén speed starts to decrease toward the ionosphere, as predicted by this theory. Similar acceleration structures have been recently measured on Mars [15], indicating the universal applicability of the alfvenon mechanism. One should also mention that the present theory of nonlinear waves, when extended with anisotropic and polybaric pressure equations [11], gives numerical results in quantitative agreement with observations of large amplitude ($\delta B/B \sim 200\%$) trains of magnetosonic solitons in a hot ($\beta \sim 10$) magnetosheath plasma [10, 16]. Plasmas in the solar atmosphere and the magnetosphere are quite similar, with the same range of plasma beta ($10^{-3} - 10^1$), and a similar altitude transition from a partly ionized, collision dominated to a fully ionized, collisionless plasma.

The numerical results obtained in this paper indicate that depending on the propagation angle and parameters V_A, B, β in different regions of the corona one could possibly create acceleration structures with electric potential drops that would account for most of the observed X-ray and radio emissions due to accelerated electrons. Typical integrated voltages across the alfvenon structures in the solar corona determined numerically are hundreds of kilovolt. Because the photospheric convection is a variable and permanently occurring process, myriads of alfvenons will be continuously recreated at different altitudes over the whole Sun, producing what is observed as the X-ray corona. Alfvenons could form bundles of threads or sheets and build up larger current structures, which should be seen in X-ray emissions when accelerated electrons thermalize in denser regions. Actually, high-resolution images from TRACE (Transition Region and Coronal Explorer) are suggestive of the existence of such threads, sheets and arcades of energized particles in the solar corona.

The present theory provides a natural link to explanations for the acceleration of the solar wind and the creation of solar flares. The solar wind originates from the coronal regions cool in X-rays, which have open magnetic field lines. Solar wind ions have energy concentrated in the drift velocity with a small thermal spread ($V_d \gg V_t$), which is consistent with acceleration by electric potential difference, and not by any stochastic or turbulent process that would produce $V_d \sim V_t$. As is seen in Fig. 1 an elementary alfvenon event ejects ions outward, providing the first kick-off for the solar wind. Typical speeds of the solar wind protons 400–800 km/s could be produced by an electric potential of 1–4 kV. A possible explanation for such small values of the acceleration voltage in coronal holes is that plasma on open field lines cannot support significant parallel electric fields.

On closed coronal loops, periodic energy releases by alfvenons driven by photospheric convection would heat plasma that will remain confined in magnetic traps. This would allow large pressure gradients and pitch-angle anisotropy to build up and support increasingly larger parallel electric fields that would accelerate ions upward. When the magnetic field tension at the top of the loop will not be able to balance the Reynolds stresses associated with flows of accelerated ions, the loop would break up, leading to plasma jets, coronal mass ejections, and a topological reconfiguration of the magnetic field. A detailed description of the mechanism for flares implied by the present theory is beyond the scope of this Letter and will be addressed elsewhere.

Application of the present model to heating of the solar corona can be summarized as follows:

(a) Dragging of magnetic field lines by non-stationary photospheric convection V_h induces magnetohydrodynamic perturbations propagating upward and carrying energy flux given by Eq. (1).

(b) An upward propagating magnetic perturbation becomes nonlinear in regions of decreasing $V_A(x)$ and forms an alfvenon, i.e. the U-shaped electric potential structure shown in Fig. 1. The size of the structures scales with λ_i and the propagation angle. For a propagation angle $\alpha \approx 0.5^\circ$ and $\lambda_i \sim 20$ m the size is: $L_\parallel \sim 6000$ km, $L_\perp \sim 50$ km, and the generated voltage is $\Phi \sim 100$ kV.

(c) The electric potential structures created in the solar corona dissipate electromagnetic energy through direct acceleration of electrons toward the chromosphere and ions out of the chromosphere.

(d) Ions accelerated outward by 1–4 kV potential drops in coronal holes would initiate outflow of the solar wind.

(e) Electrons accelerated toward the chromosphere by a potential difference up to hundreds kV (on closed loops) produce X-ray corona, radio emissions, and evaporation/heating of the chromosphere.

(f) The processes described in (a)-(e) would repeat as long as there is variable photospheric convection pumping the energy flux (1) into regions of a decreasing Alfvén speed.

The alfvenons introduced in this Letter appear to be effective and spectacular converters of electromagnetic energy flux into kinetic energy of particles. They have been measured by numerous spacecraft in the terrestrial magnetosphere, where they accelerate auroral electrons toward the ionosphere to tens of keV, and are detected also in the martian environment. They appear to be of universal importance for astrophysical plasmas and must occur also in the solar atmosphere, where they can account for the acceleration and heating of plasma in the solar corona.

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[1] G. L. Withbroe and R. W. Noyes, Ann. Rev. Astron. Ap. **15**, 363 (1977).
[2] M. Kuperus, J. A. Ionson, and D. S. Spicer, Ann. Rev. Astron. Ap. **19**, 7 (1981).
[3] E. R. Priest, *Solar Magnetohydrodynamics* (Dordrecht:Reidel, 1982).
[4] H. Zirin, *Astrophysics of the Sun* (Cambridge University Press, 1988).
[5] E. N. Parker, Ap. J. **330**, 474 (1988).
[6] U. Narain and P. Ulmschneider, Space Sci. Rev. **75**, 453 (1996).
[7] C. H. Mandrini, P. Demoulin, and J. A. Klimchuk, Ap. J. **530**, 999 (2000).
[8] M. J. Aschwanden, *Physics of the Solar Corona* (Springer, 2004).
[9] G. H. Fisher, D. W. Longcope, T. R. Metcalf, and A. Pevtsov, Ap. J. **508**, 885 (1998).
[10] K. Stasiewicz, J. Geophys. Res. **110**, A03220 (2005).
[11] K. Stasiewicz, Phys. Rev. Lett. **95**, 015004 (2005).
[12] K. Stasiewicz, Phys. Rev. Lett. **93**, 125004 (2004).
[13] D. A. Gurnett, in *Critical Problems of Magnetospheric Physics*, edited by E. R. Dyer (AGU, 1972), pp. 123–138.

[14] G. Paschmann et al., Space Sci. Rev. **103**, 1 (2003).
[15] R. Lundin et al., Science **311**, 980 (2006).
[16] K. Stasiewicz, Geophys. Res. Lett. **31**, L21804 (2004).